Butts, M.B. Q-M. Lu, J. Høst-Madsen (2005) Exploiting the Potential of Distributed Modelling for Flood Forecasting and Management.(Invited paper) International Conference on Reservoir Operation and River Management (ICROM), Guangzhou, China September 17-23, 2005

Exploiting the Potential of Distributed Modelling for Flood Forecasting and Management

MICHAEL BUTTS[1], QIAN-MING LU[2], JACOB HØST-MADSEN[1]
[1]River & Flood Management Department, DHI Water & Environment, Agern Alle 5, DK-2970 Hørsholm, Denmark, Tel: +45 45169200, Fax: +45 45169292, mib@dhi.dk
[2]DHI China, 27th B, Wan Ping Mansion, 278 Wu Xing Road, Shanghai, 200030, China, lqm@dhi.dk

Abstract. New opportunities for distributed hydrological modelling applied to flood forecasting are emerging from new sources of spatially distributed data such as weather radar, satellite platforms, and high-resolution meteorological models. The availability of GIS tools, together with national and global databases allows scientists and practising hydrologists the opportunity to access and use enormous quantities of spatial and temporal data. With the exponential increase in computing power it is feasible to apply high resolution distributed hydrological models to a range of water resource problems including flood forecasting. State of the art operational hydrological forecasting models usually rely on conceptual or empirical models, based to a greater or lesser degree on the physics of rainfall-runoff. By contrast state-of-the-art hydrological modelling is represented by fully distributed physically based models, which exhibit a much greater level of complexity. In practice, the level of complexity required for hydrological modelling will depend on the available catchment data, the important catchment rainfall-runoff processes and the problem to be solved. Therefore distributed models are needed which can adapt to the available data and to different levels of complexity. The goal of this paper is to show how some of these new opportunities are being used to improve flood forecasting.

Key Words. Flood forecasting, distributed modelling, satellite remote sensing weather radar, uncertainty

1 INTRODUCTION

A number of recent technological developments have created renewed interest from both researchers and hydrological practitioners in the application of distributed modelling to flood management and flood forecasting. With the increasing availability and rapid technological development of satellite remote sensing, hydrologists have recognised the potential benefits of employing satellite data in hydrology and water resources. In particular satellite remote sensing provides much sought after spatially distributed information for distributed hydrological modelling. Networks of operational weather radar platforms provide high-resolution spatially distributed precipitation estimates and short-term precipitation forecasts. New opportunities for applying numerical meteorological models at greater temporal and spatial resolution exist today that did not exist a few years ago. These models not only provide useful qualitative information about approaching flood-producing storms but more importantly quantitative precipitation forecasts.

As a result of these technological developments there are a number of challenging scientific questions related to these opportunities such as what is the nature and impact of spatial variability of basin physical characteristics and meteorological forcing? What role does uncertainty play in achieving benefits from distributed models and what level of model complexity is required? More importantly for practising hydrologists is whether the potential benefits provided by these new developments can be translated into practical benefits. In the paper, we examine how some of these opportunities are being exploited for flood management and flood forecasting using selected case studies to illustrate what benefits, if any, can be achieved.

2 SATELLITE REMOTE SENSING (RS) DATA IN FLOOD FORECASTING

The combination of satellite-based remote sensing and distributed hydrological modelling provides a powerful tool for hydrological prediction and forecasting. Firstly it is possible to obtain direct measurements of the state of the catchment, including flooding conditions, surface temperature for monitoring evapotranspiration, soil moisture conditions, snow coverage and snow water content, etc. Secondly RS data is integrated over an area in contrast to the point data usually obtained from traditional monitoring networks. Since many distributed hydrological models both use hydrological parameters integrated over a numerical grid and make predictions on the same grid, RS can provide data directly at the modelling scale. The particular strength of RS data is that it is often the only source of information, in remote areas such as deserts and areas with low network density. The increasing availability of RS data opposes the global trend in the reduction of traditional monitoring networks. (UN/WWAP, 2003). Finally, RS data is available in near real-time, which is one of the reasons it has been a normal part of weather forecasting systems for many years.

2.1 Limitations of satellite remote sensing data in hydrology

There are a number of limitations that must be addressed in the application of remote sensing data for hydrological simulation. Firstly the cost of obtaining the data is still relatively high when large quantities are needed, limiting its widespread use particularly in developing countries. There is therefore a corresponding lack of technical skills in the same countries as the collection and processing of remote sensing data is still a specialist task. At present many of the existing platforms are focussed on geophysical applications within oceanography, climatology, and meteorology, so hydrological applications are generally only a secondary product. This means that the frequencies and frequency ranges actually measured, limit the hydrological quantities that can be derived. The most challenging aspect of the application of remote sensing is that the relationships between the satellite measurement and the physical quantity of interest are often indirect. To derive the physical quantities requires either the introduction of interpretative models or local ground measurements or both. The type of satellite used (geostationary or orbiting) and the height determine the spatial and temporal resolution of the RS data. In general many hydrological applications require both higher resolution and more frequent measurements than are currently available. As well as these more general limitations there are a number of more specific limitations depending on the satellite used and the data of interest, Engman 2000. For example cloud cover may prevent the use of satellite imagery for flood inundation. On the other hand there are a number of planned and proposed sensors and platforms with generally improved spatial resolutions, narrower and more specific spectral bands and more in the microwave spectrum. Several global projects have been initiated where data is free and easily accessible on the web. Nevertheless, further exploitation of both routine satellite remote sensing data and emerging developments are required to demonstrate their practical application.

2.2 Application of GIS and satellite remote sensing to flooding in Bangladesh

Bangladesh is subject to frequently flooding and often catastrophic flooding with recent extreme floods in 1987, 1988, 1998 and 2000, (Brammer 1999; Chowdury, 2000).

Bangladesh is a low-lying country on the delta formed at the confluence of the three major rivers the Ganges, the Brahmaputra and the Meghna, Figure 1. The catchment area of the Ganges, Brahmaputra and Meghna Rivers are 907,103 km^2, 583,103 km^2 and 65,103 km^2, respectively, of which only 8% lie in Bangladesh, Jakobsen et al., 2005.

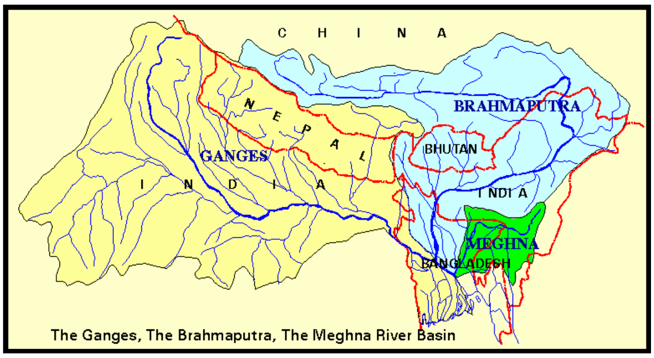

Figure 1 Bangladesh in relation to the Ganges, Brahmaputra and Meghna River basins

2.3 Flood forecasting in Bangladesh

One response to the frequent and often catastrophic flooding in Bangladesh is the application of flood forecasting. Since the early nineties a flood forecasting and warning system based on hydrodynamic modelling of the river system and hydrological modelling of the rainfall-runoff processes has been applied in Bangladesh, (Jørgensen and Høst-Madsen 1997). Operational forecasts are made on a daily basis in the monsoon season through the Flood Forecasting and Warning Centre (FFWC). FFWC operates "Flood information Centre" as focal point in connection with Disaster Management both for cyclones and floods, (http://www.ffwc.net/). The flood forecasting hydrometric network consists of more than 60 water level and rainfall stations. Data is collected both manually and via telemetry systems. This data is acquired by the MIKE FLOODWATCH real-time databases for display and monitoring, for real-time flood forecasting of both water levels and discharge within the river network and flood extent in the surrounding floodplains. The flood forecasting is carried out using the MIKE 11 model (Havnø et al. 1997). The current model covers most of Bangladesh including some 156 rainfall-runoff catchments, and a detailed representation of the river system.

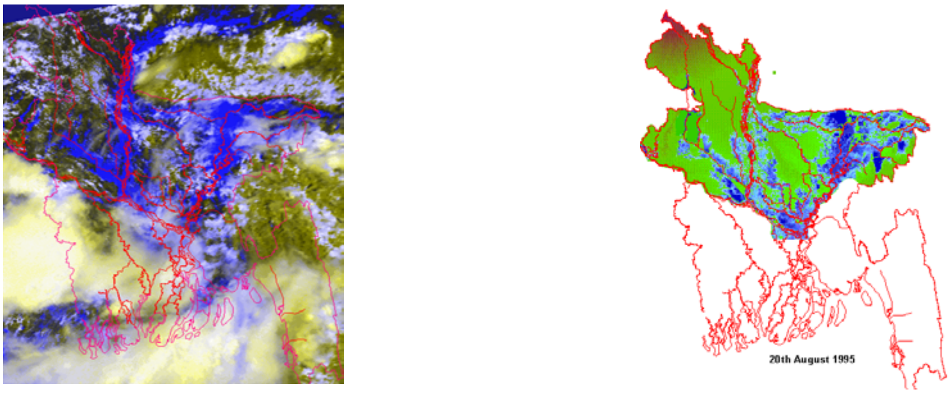

Figure 2 Comparison of the flood extent derived using the flood mapping with MIKE 11 GIS and satellite imagery showing the cloud cover and flooded areas during the 1995 floods.

Extensive calibration and validation of the model has been carried out (Jørgensen and Høst-Madsen 1997) against both water level and discharge measurements. An evaluation of the model results (Chowdhury, 2000) has demonstrated their usefulness during flood events. One of the potentially most powerful uses of satellite remote sensing is to provide independent validation of the spatial predictions made by hydrological models. In this case the prediction of flooding outside of the river system is difficult to capture using traditional monitoring methods. Since in Bangladesh extensive flooding occurs outside the river system, it is important to capture this correctly for flood forecasting. A comparison with remote sensing images provides a strong test of the predictive ability of the forecasting model. Examples of the independent validation of the simulations of both flood extent and flood depth can be obtained using estimates of flood extent (Figure 2) and flood depth (Figure 3) from satellite imagery. The flood depth is deduced by combining a digital elevation model with the flood map based on satellite data.

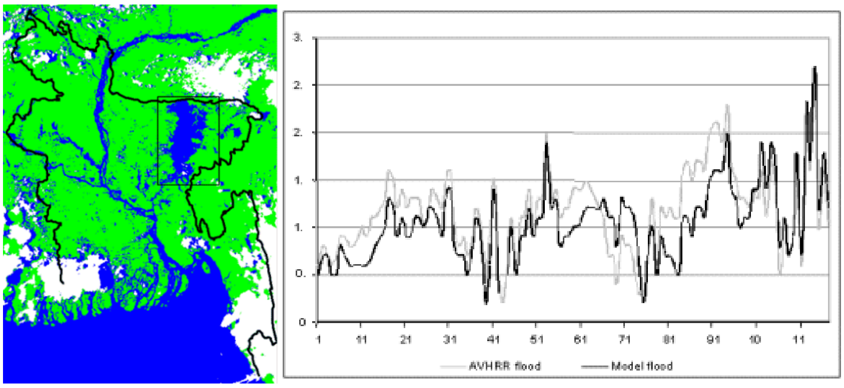

Figure 3 Comparison of flood depth during September 2002 along a 120 km transect through the inundated area in north east Bangladesh estimated using the forecasting mode (dark line) and satellite imagery(grey line).

2.4 Satellite-based precipitation nowcasting

The current forecasting system is based on operational data and forecasts within Bangladesh. A key source of uncertainty therefore is the forecasts of the behaviour of the inflows from the Ganges and Brahmaputra rivers at the boundaries between Bangladesh and India. At present only limited traditional operational data is available outside Bangladesh. Nor is it currently feasible to gather detailed traditional rainfall information over the extensive Ganges, Brahmaputra and Meghna basins. On the other hand daily rainfall estimates in the tropics have been made using geostationary satellites like GOES (US), METEOSAT (EU) and GMS (Japan). Therefore one method of improving the boundary forecasts is to use the daily rainfall estimated over the Ganges and Brahmaputra basins from satellite imagery as input into a large-scale hydrological model of these basins. As a first step, the feasibility of such an approach was examined. The satellite data in this feasibility study were recorded by the geostationary METEOSAT 5 satellite for the four months of the monsoon (June- September) of 1999. Thermal Infra-Red (TIR) data were provided by EUMETSAT, Darnstadt, free of charge at two hour intervals on a 5 km grid scale, Dybkjær, 2003.

A relatively simple approach was adopted for the large-scale modelling of the Ganges and Brahmaputra basins. Each basin was divided into 14 sub-catchments, using a 1 km global DEM to delineate the catchment drainage boundaries according to response time. A conceptual rainfall-runoff model (NAM) was used to model the hydrological processes and a simple time delay was introduced to account for the channel routing. NAM has been widely used for flood forecasting (Havnø et al, 1995) and requires only moderate data inputs. Two discharge stations outside of Bangladesh were used to examine the predictions made using this simple approach with satellite-based rainfall, Pankha and Noonkhawa representing the downstream end of the Ganges and Brahmaputra rivers, respectively. Figure 4 shows the simulated discharge using the satellite-based rainfall against the observed discharge for the Ganges and Brahmaputra stations respectively. Given the relatively crude modelling approach used here the results shown are promising. Some discrepancies at the Pankha station were expected because of the operation of a reservoir, water transfer scheme upstream of this station. At the Noonkhawa station scaling of the estimated rainfall was required to achieve satisfactory results indicating that local calibration is required. However these initial results suggest that further work should be carried out to develop this approach operationally.

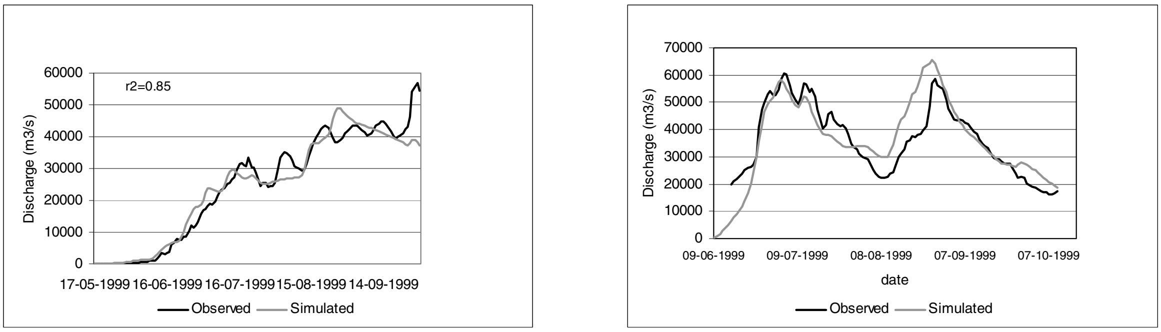

Figure 4 Simulated and observed discharge at the Pankha (Ganges) station (left) and at the Noonkhawa (Brahmaptura) station (right).

3 WEATHER RADAR AND DISTRIBUTED HYDROLOGICAL MODELLING

While distributed modelling has a number of potential benefits it appears that further work is required to achieve this potential for operational modelling. Refsgaard and Knudsen (1996) compared a complex distributed model, a lumped conceptual model, and an intermediate complexity model on data-sparse catchments in Zimbabwe. Their results could not strongly justify the use of the complex distributed model. Bell and Moore (1998) evaluate variants of a simple grid-based distributed model against a lumped model used operationally in the UK. They find that a well-designed lumped model is preferable for operational purposes. A recent study of initiated by the US National Weather Service (NWS) Distributed Model Intercomparison Project (DMIP) represents perhaps the first organised and published comparison of distributed models amongst themselves and to a widely used lumped model, (Smith et al. 2004). One of the key findings, (Reed et al., 2004) was that "although the lumped model outperformed distributed models in more cases than distributed models outperformed the lumped model, some calibrated distributed models can perform at a level comparable to or better than a calibrated lumped model (the current operational standard)." These results suggest that further work is required in exploring different distributed model formulations.

Within the EU 5th framework project FLOODRELIEF (http://projects.dhi.dk/floodrelief/) a general modelling framework has been developed, which allows alternative model structures for the rainfall-runoff processes and channel routing to be explored (Butts et al., 2004a). Any evaluation of the accuracy of deterministic hydrological models for hydrological simulations and forecasting must address four sources of uncertainty. They are the random or systematic errors in the model inputs or boundary condition data, random or systematic errors in the recorded output data, uncertainty due to sub-optimal parameter values and errors due to incomplete or biased model structure. A critical choice in applying mathematical models to hydrological problems is the selection of model structure. Selecting an appropriate model structure encompasses determining the most significant hydrological processes to be described, the mathematical description of these processes and their spatial representation.

In most practical engineering problems, hydrologists attempt to identify the important processes and select a model system accordingly. Once this selection is made, further efforts to examine the impact of adopting different model structures are seldom made. Instead emphasis is usually placed on evaluating the impact of parametric uncertainty. Very few studies have examined in a systematic way the significance of model structure uncertainty in relation to the other sources of uncertainty. The essential difficulty for hydrological practitioners is that most current modelling tools provide very limited options for exploring different model structures. Furthermore there is a need to match the model structure to the level of complexity to the particular application, the available data sources and the accuracy requirements. To address these requirements a new hydrological modelling tool has been developed that allows the modeller to select which processes require modelling, the level of conceptualisation, the degree of lumping and hence the level of complexity that is necessary for a particular application. The tool provides a process-based description of the rainfall-runoff and channel routing based on the MIKE SHE and MIKE 11 hydrological modelling concepts. The modelling paradigm of Freeze and Harlan, 1979 used in MIKE SHE is extended to include lumped and conceptual descriptions to supplement the original distributed physics-based flow equations. An investigation of the impact of model structure on simulation uncertainty using this tools was carried out within the DMIP project using this tool developed within the FLOODRELIEF project, Butts et al. 2004a & b.

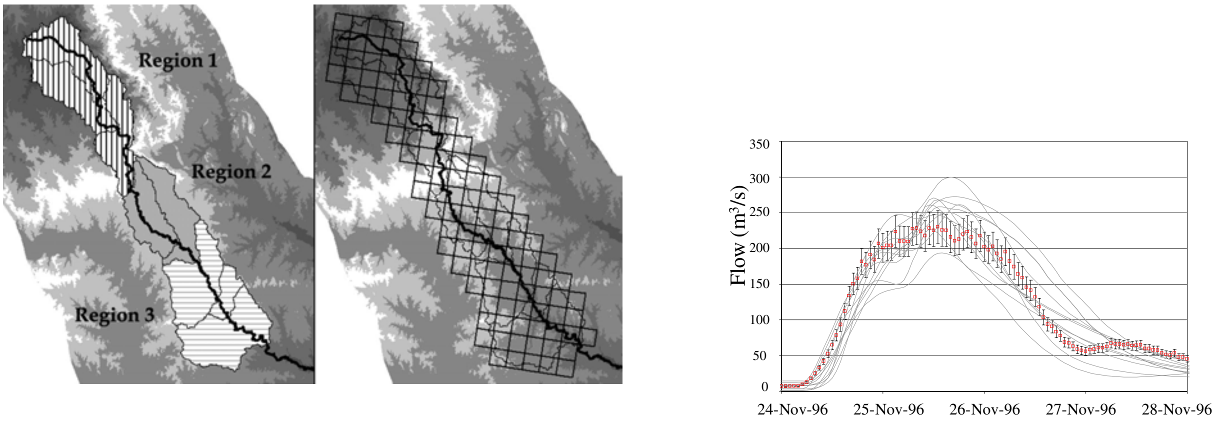

Figure 5 Different model representation were used in this study for the Blue River basin. The figure on the left shows the 8 subcatchments used in conceptual modelling and the parameter regions used for calibration. The figure in the t middle shows the 4-km NEXRAD grid used for the grid-based modelling. The behaviour of the 10 different model structures used in this study (grey lines) and the estimated measurement uncertainty (error bars)

3.1 DMIP Study area

The study area used here is one of the test basins within the DMIP project organised by the Hydrology Lab of NWS, http://www.nws.noaa.gov/oh/hrl/dmip/, the 1232 km^2 Blue river basin in Oklahoma,
Figure 5. It is of interest for distributed hydrological modelling because of its unusual aspect ratio, soil variability and the availability of distributed radar-based rainfall. The Blue river basin is located in south-central Oklahoma and flows into the Red River at the Texas-Oklahoma border. The watershed is semi-arid, with significant convective rainfall events. Distributed rainfall data is available in the form of NEXRAD gridded data provided at hourly intervals at a spatial resolution of 4 km by 4 km. The new modelling tool was used, firstly to

test the performance of the different model structures and secondly to evaluate the model structure uncertainty compared to other sources of uncertainty. To this end 10 different model structures were identified as plausible model structures. The different model structures included both lumped and distributed routing, lumped, subcatchment-based and distributed rainfall-runoff models, grid-based modelling using physics-based flow equations, different conceptual process descriptions and lumped, subcatchment-based and gridded radar-rainfall input, Butts et al. 2004a.

To evaluate their performance each model structure was fitted to data in the calibration period and then evaluated against measurements in the validation period. Each model structure was fitted to the calibration period using automatic parameter estimations based on the Shuffled Complex Evolution and multiple objectives, Madsen 2000. The average error and RMSE were used as the calibration objectives. The split sample testing approach used here can then be used as a means of selecting the best model structure for the purpose – in this case flood forecasting.

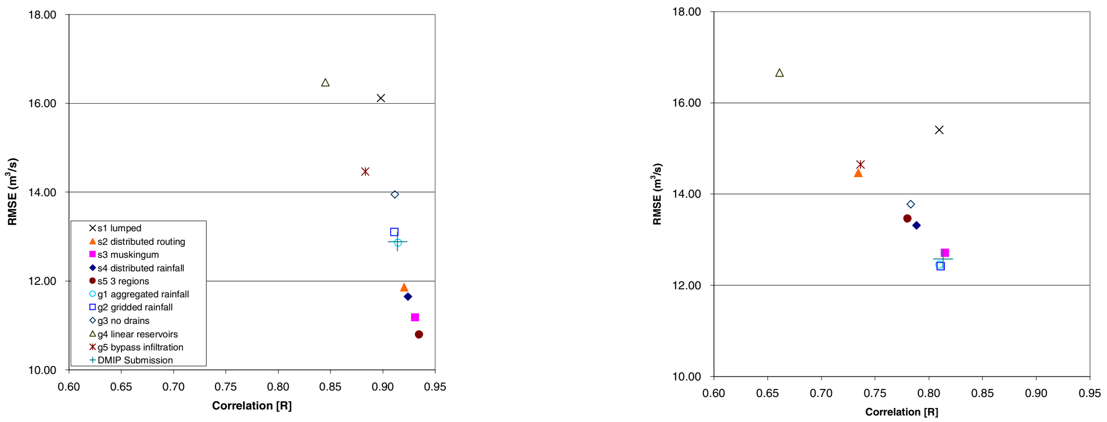

Figure 6 Root means square error (RMSE) and correlation (R) for the calibration (upper) and validation (lower) period

The simulated hydrographs using the different models for a major flood is shown in Figure 5. The performance of each of the selected model structures is shown in Figure 6. From an examination of these figures it is clear that model performance is strongly dependent on model structure. Significantly different discharge hydrographs are produced by these different structures even though they are calibrated against the same objectives. The lumped description has a high correlation in both the calibration and validation but a poor RMSE compared to the distributed model structures. There are several interesting observations that need further investigation. Firstly the most significant improvement in model performance is achieved by introducing distributed routing into the lumped rainfall-runoff model (s1 to s2). The best performing model appears to be s3 which used subcatchment-based rainfall distribution. Interestingly there appeared to be little difference when using the grid-distributed radar data or the sub-basin rainfall in the grid-based model formulations (g1 vs g2). This seems to suggest that the extra spatial information in the NEXRAD data does not significantly improve the simulation accuracy. This is contrary to our expectations and may be a result of limitations in the grid-based model.

4 CONCLUDING REMARKS

Intuitively higher resolution meteorological information and hydrological models are expected to lead to more accurate simulations. Within the EU 5th framework project FLOODRELIEF investigations are being carried out to evaluate these expected improvements including the application of high resolution meteorological modelling. However to achieve this, the spatial variability at different scales in the meteorological driving forces, the hydrological properties, and the hydrological processes must be represented consistently in the distributed hydrological models to match the problem to be solved and the data available. One of more of these factors may be limiting and it is difficult to determine a priori.

One strategy identified in this paper is to develop distributed hydrological models that provide different methods of representing of spatial variability, different levels of model complexity, and different process descriptions within the same framework. Such models can be used to explore the associated science questions and can be readily adapted to address different water resource problems depending on the goals of the investigation and the data available.

5 REFERENCES

Bell, V. A. and R.J. Moore, 1998. A grid-based distributed flood forecasting model for use with weather radar: Part 2. Case studies. Hydrology and Earth Systems Sciences 2(3), 283-298.

Brammer, H. 1990. "Floods in Bangladesh I. Geographical background to the 1997 and 1998 floods." *The Geographical Journal* 156, No. 1: 12-22.

Butts M.B., J Hoest-Madsen and J.C. Refsgaard, 2002: Hydrologic Forecasting, *Encyclopaedia of Physical Science and Technology* 3rd Edition.

Butts, M. B., J. T. Payne, M. Kristensen and H. Madsen. (2004a). An evaluation of the impact of model structure and complexity on hydrological modelling uncertainty for streamflow prediction. *Journal of Hydrology*, **298**, 242-266.

Butts, M. B., J. T. Payne, and J. Overgaard. (2004b). Improving streamflow simulations and flood forecasts with multimodel ensembles *Proc. of the 6th International Conference on Hydroinformatics - Liong, Phoon and Babovic (eds).* World Scientific Publishing Company, ISBN 981-238-787-0, pages 1189-1196

Chowdhury, Md. R. 2000. "An assessment of flood forecasting in Bangladesh: The experience of the 1998 flood." *Natural Hazards* 22: 139-163.

Dybkjær, G., 2003.A simple self-calibrating cold cloud duration technique applied in West Africa and Bangladesh. *Danish Journal of Geography* 103(1), 83-97.

Engman, E.T., 2000, Soil Moisture, in: *Remote Sensing in Hydrology and Water Management* by Schultz, G.A. and Engman, E.T. (Eds), Springer, Berlin.

Havnø, K., Madsen, M.N and Dørge J.1995: MIKE 11 – A Generalized River Modelling Package, In: *Computer models of Watershed Hydrology*, V. P. Singh ed., Water Resources Publications, Colorado, USA: 733-782.

Jakobsen, F., A.K.M. Z. Hoque, G.N. Paudyal, Md. S. Bhuiyan. (2005) Evaluation of the short-term processes forcing the Monsoon river floods in Bangladesh. *Water International (IWRA)* **30** (3), Accepted for publication September, 2005.

Jørgensen, G and J.Høst-Madsen, 1997. Development of a flood forecasting system in Bangladesh, *Proc. of the European Water Resources Association Conference: Operational Water Management*, Copenhagen, 3-6 September, 1997 (Eds. J.C. Refsgaard and E.A. Karalis, 137-148.

Madsen, H. 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. *Journal of Hydrology*, **235**: 276-288.

Reed S., Koren V., Smith M., Zhang Z, Moreda F., Seo D-J and and DMIP Participants, Overall distributed model intercomparison project results, *Journal of Hydrology*, Volume 298, Issues 1-4, 1 October 2004, Pages 27-60.

Refsgaard, J. C. and J. Knudsen 1996: Operational validation and intercomparison of different types of hydrological models, *Water Resources Research*, **32(7)**: 2189-2202.
Smith M.B. , Seo D-J, Koren V. I., Reed S.M. , Zhang Z, Duan Q, Moreda F. and Cong S., The distributed model intercomparison project (DMIP): motivation and experiment design, *Journal of Hydrology*, **298**, Issues 1-4, 1 October 2004, Pages 4-26.
UN/WWAP (United Nations/World Water Assessment Programme). 2003. *UN World Water Development Report: Water for People, Water for Life.* Paris, New York and Oxford, UNESCO (United Nations Educational, Scientific and Cultural Organization) and Berghahn Books.